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A LITERATURE SEARCH AND EVALUATION OF ANGLED WALL JET DEFLECTION

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It has been suggested that the direction and shape of bore evacuator jets can be affected by the angle the evacuator holes make with the tube wall. A literature search was conducted to discover and evaluate what is known about the deflection of wall jets. Preliminary findings indicate that the Coanda effects outside the hole have little effect in drawing three-dimensional jets closer to the wall. Some jets were found to deflect away from the wall because of the asymmetric distribution on the hole lip.

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INTRODUCTION

A literature search was conducted to determine what role the Coanda effect plays in the performance of a bore evacuator. Several references on supersonic asymmetric nozzles and on elliptical jet entrainment were also found to be useful in the analysis of a bore evacuator. The results are presented in this report.

SUBSONIC COANDA FLOW

Many studies (refs 1-8) have been conducted on subsonic Coanda flow. The majority of the papers (refs 1-5) investigated two-dimensional (2-D) unventilated Coanda flow. No information was found on three-dimensional (3-D) flow, and only two papers (refs 6 and 8) were found on ventilated Coanda flow. Sawyer's "Two-Dimensional Reattaching Jet Flows Including the Effects of Curvature on Entrainment" (ref 2) and Bourque and Newman's "Reattachment of a Two-Dimensional Incompressible Jet to an Adjacent Flat Plate" (ref 3) are particularly informative.

These references mostly confirmed what was intuitively expected. The deflection of a wall jet and attachment to the wall are due to a low pressure recirculatory region between the jet and the wall. Attaching jets have a much lower entrainment than free jets. Attachment occurs closer to the nozzle as the angle of the jet to the wall decreases. The distance between the nozzle and reattachment point increases with increasing ventilation. Finally, an unexpected result is an increase in the flow rate through the nozzle due to the presence of an inclined wall. This last result is of limited use because the bore evacuator nozzle flow is primarily supersonic. If a model for the subsonic flow through the bore evacuator is to be explored, then this phenomenon would be valuable. In any event, the augmentation is at most only 6 percent.

One of the major differences between the 2-D and 3-D wall jet is the effect of ventilation. In the 3-D case, fluid can flow around the jet into the region between the wall and jet. This flow results in a pressure closer to ambient in the recirulatory region than the 2-D flow. References 6 and 8 include ventilation, but do not include a comparison of ventilation flow rate to a 3-D jet ventilation flow rate.

SUPERSONIC COANDA FLOW

Two sources (refs 9 and 10) on supersonic Coanda flow were found. The Sokolova study (ref 9) is of little value due to the difficulty of interpreting the results. The Gregory-Smith and Gilchrist investigation (ref 10), however, is understandable and contains many insights.

The Gregory-Smith and Gilchrist paper experimentally investigated a 2-D supersonic jet flowing along a curved surface as shown in Figure 1. The jet followed the wall profile until the pressure ratio (P_0/P_a) was increased to a critical value. At the critical pressure ratio, the jet no longer followed the wall but issued forth from the nozzle as a free jet. The critical pressure ratio required to switch the flow from free jet flow to Coanda flow was always less than the critical pressure ratio required to switch the flow from Coanda to free jet flow.

Another aspect of the Gregory-Smith and Gilchrist paper is the effect of the jet thickness on the critical pressure ratio. They found that as the jet thickness decreased, the pressure ratio needed to establish free jet flow increased. If this relationship between jet diameter and pressure ratio at the onset of the Coanda effect is also true for the 3-D flows, then the onset of the

Coanda effect (if any) will occur at lower pressure ratios in the cannons than in the bore evacuator experiment due to the larger diameter nozzles in the guns.

Due to the effects of ventilation on 3-D jets and the differences in geometry, only trends indicating when the Coanda effect will occur can be predicted. The occurrence of the Coanda effect is believed to reduce the augmentation of bore flow due to the increased skin friction and reduced entrainment. The predicted effects of augmentation on a bore flow due to the Coanda effect are compared with experimental results below.

Some evidence of the Coanda effect was seen in the collected data from the bore evacuator experiment (ref 11). As the angle ϕ, shown in Figure 2, increased from 135 to 150 degrees, the augmentation increased for all pressure ratios. The augmentation, however, decreased with a further increase of ϕ to 160 degrees. These findings concur with the expectation that the Coanda effect will occur at the larger angles. Another observation indicating the Coanda effect was the reduction of augmentation with the reduction of pressure ratio for the 150-degree data. This reduction only occurred between the two smallest bore evacuator pressure ratios. This checks with the tendency for the Coanda effect to be present at the lower pressure ratios. The data that support this finding, however, are suspected to contain some major calculation errors. A more trustworthy source of information on the 150-degree nozzle would be the pictures of angled jet flow provided by H.T. Nagamatsu et al. (ref 11). These pictures showed no Coanda effect for any pressure ratio.

Some trends in augmentation that would be expected due to the Coanda effect were not found in the data. The Coanda effect was found in Reference 10 to attach the jet to the wall at the lower pressure ratios. A dramatic increase in augmentation would be expected to occur after the pressure ratio increased over the critical value. Yet, a gradual decrease in augmentation was observed, revealing no evidence of a switch from Coanda flow to free jet flow. The critical pressure ratio, however, may not have been reached in the experiment for the 160-degree nozzle.

One 3-D experimental study, "Influence of Nozzle Asymmetry on Supersonic Jets" (ref 12) was found. The two cases of interest were the inclined nozzle of 26.6 and 45 degrees shown in Figure 3. Pressure ratios of 2.2, 2.8, 3.4, and 4.0 were investigated. The investigation did not include the effects of a wall present on the jets, thus eliminating the effects of Coanda.

The supersonic jet deflected after exiting the nozzle as shown in Figure 4. This deflection was also observed in the photograph of the free jet in Reference 10. The photographs of a supersonic wall jet provided by H.T. Nagamatsu et al. (ref 11) also had a measurable deflection.

The deflection angle β depended on the angle of the nozzle α and the pressure ratio. In the α = 26.6-degree nozzle run, α remained fairly small and constant with increasing pressure ratio. For the α = 45-degree nozzle, α varied between 2.5 and 12.5 degrees for pressure ratios of 2.2 and 4.0, respectively. This jet angle change resulted in a change in momentum of the jet.

The above observed behavior of the nozzle jet can be explained using a control volume approach. Figure 4 shows four nozzles of different α. The straight nozzle jet has no deflection because the tube wall pressures are balanced. The deflection of the jet is due to the wall pressure from the lip on the jet. The total force on the jet is a function of the lip area and the average lip pressure. If the lip is very small (Figure 4b), the average wall pressure will be nearly half of the upstream pressure, but the area will be small. The result is a small force and a small deflection of the jet. As the lip size increases (Figure 4c), the deflection increases due to an increase in area with a small decrease in average pressure. As the lip size becomes very large (Figure 4d), the deflection angle decreases due to a large decrease in average pressure. This large decrease in average pressure is due to a subambient pressure at the tip of the nozzle bringing the average pressure down nearly to an ambient pressure. The increase in deflection with increasing pressure ratio can be explained by an increase in the average pressure.

ELLIPTICAL JETS

Three references of subsonic elliptical jets were found (refs 13-15). The Ho Chih-Ming and Gutmark paper (ref 14) is the most informative. They found that the entrainment of elliptical free jets is much greater than that of circular jets. Increased entrainment is desirable because it results in a higher pumping efficiency in the bore evacuator.

The work of Wlezien and Kibens (ref 12) on asymmetric nozzles indicates that slanted supersonic nozzles produce elliptical-shaped jets with a major axis in the same direction as the vertical axis of Figure 3. The aspect ratio of the elliptical shape was found to vary with pressure ratio and α. However, the paper does not give enough details to determine the extent of the variation. A modification of the nozzle hole to an elliptical shape may enhance the existing elliptical shape of the jet. This, in turn, would improve the entrainment and the effectiveness of the bore evacuator.

CONCLUSION

It is apparent that small changes in the wall-jet flow have a dramatic effect on the induced flow in a bore evacuator. The changes in the nozzle flow can be predicted from the results of the references cited in this report. These predictions, however, are valid only for a very small range of pressure ratios and nozzle angles. Even within these ranges, the predictions, while better than nothing, are of questionable accuracy.

Experiments should be conducted to better determine the deflection of the jet with α and pressure ratio. These experiments would also establish the relationship between the onset of the Coanda effect and pressure ratio and α. A drawing of the proposed setup, including the location of the pressure taps, is shown in Figure 5. A high concentration of pressure taps is located in the nozzle lip because this pressure distribution causes the deflection of the jet. A few pressure taps farther up the nozzle are included to find the location of the sonic flow. The pressure taps outside the nozzle give the upstream and downstream wall pressures and may indicate the rate of ventilation of the jet. Schlieren pictures of the jet flow should be taken to measure the deflection angle and to determine the onset of Coanda.

Some of the major points that should be considered in the experiment include the nozzle diameter and the diameter-to-length ratio. The location of sonic flow depends on the diameter-to-length ratio. The diameter of the nozzle should be as large as possible to install pressure taps and to increase the quality of the Schlieren pictures. The major drawback to increasing the diameter of the nozzle is that the onset of supersonic Coanda flow was found to depend on the width of the jet. Therefore, a larger diameter nozzle may cause the onset of Coanda to occur at a much lower pressure ratio. If a separate run could be made to observe only Coanda effects with the full nozzle diameter of a bore evacuator, then this problem would be eliminated.

In the future, a study of the elliptical jet may be in order to determine whether the increased efficiency of the bore evacuator is worth the added expense in production. Experiments, similar to the above-mentioned, should be conducted with varying ratios of major to minor axis widths.

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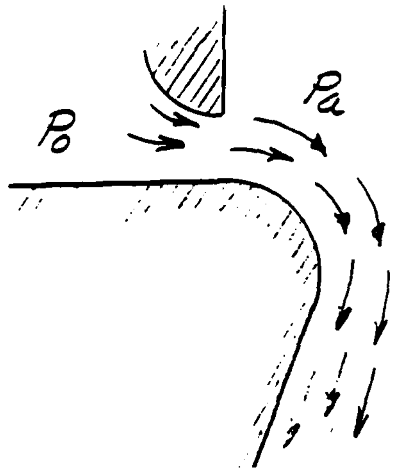

Figure 1. Supersonic flow along a curved surface.

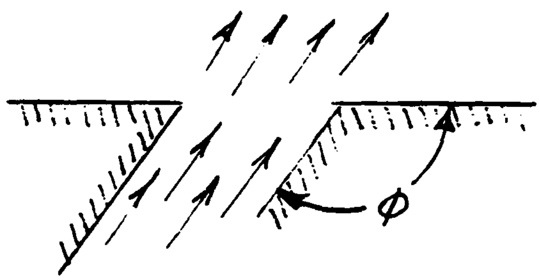

Figure 2. Bore evacuator hole.

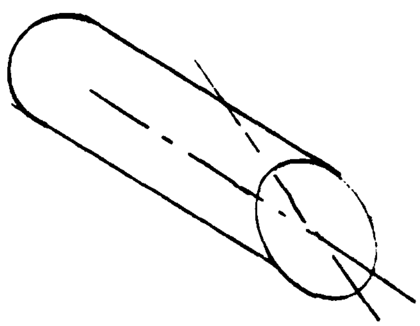

Figure 3. Nozzle with angled exit.

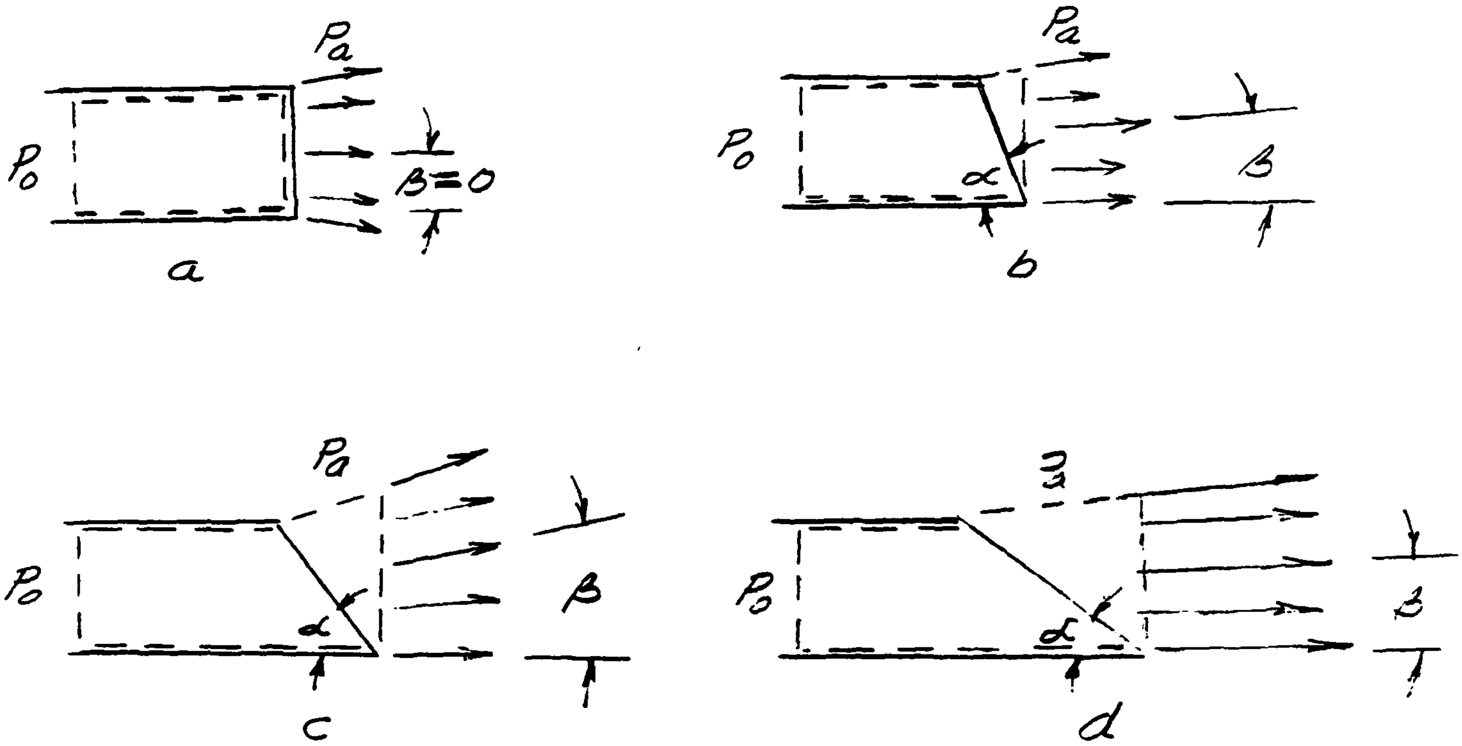

Figure 4. Side view of jet.

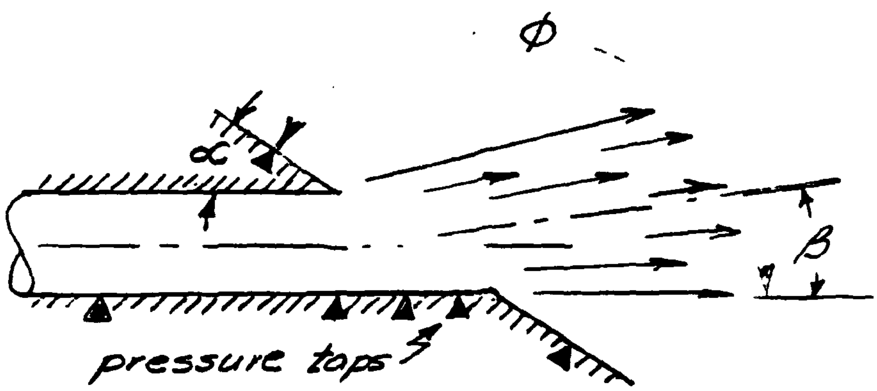

Figure 5. Effect of nozzle angle on jet deflection.

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